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SIMULATION OF AN OBLIQUE COLLISION OF A LOCOMOTIVE AND AN INTERMODAL CONTAINER

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ABSTRACT

This paper presents an approach to modeling an oblique collision of a locomotive and an intermodal container. Previous studies of offset and oblique train collisions have used one and two-dimensional models to determine the trajectories of the equipment during the collision (Mayville, et al, 1995, Tyrell, et al, 1997). This analysis uses a three-dimensional model to determine the trajectories of the equipment.

In the collision scenario of concern, an intermodal container impacts the outboard corner of the short hood of a wide-nose locomotive above the deck. An impact element has been used in the collision dynamics model to transfer contact load to the short hood of the locomotive. A detailed non-linear finite element model has been developed to characterize the force-crush behavior of the short hood. These results determine the parameters that connect the impact element to three-dimensional lumped-masses that represent vehicles in the consist. The collision dynamics analysis includes the influence of the locomotive suspension and the trailing locomotive.

The model has been used to evaluate the influence of short hood design on intrusion into the operator's cab, the deceleration of the locomotive during the collision, and whether derailment of the locomotive occurs as a consequence of the collision. Results indicate that short hood strength can be increased significantly above the strength of the current design without derailing the locomotive in this collision scenario. Increased short hood strength increases the maximum closing speed that can be sustained without intrusion into the operator's cab, while the deceleration of the operator's cab remains relatively low.

INTRODUCTION

A significant number of severe train collisions in which the impacting vehicles are initially offset or oblique have occurred over the past few years. A collision is oblique when the longitudinal centerlines of the colliding cars are not parallel and is offset when the centerlines are parallel, but do not lie on the same line. These conditions typically result in complex vehicle trajectories. Large lateral displacements and yaw rotations of the vehicles coupled with equipment damage create the potential for injuries and fatalities. Such collisions require complex models to simulate the motion and to evaluate the effectiveness of design modifications intended to improve crashworthiness.

On January 18, 1993, near Gary, Indiana, an offset collision occurred between two multiple-unit (MU) commuter rail trains on a gantlet track on a bridge (NTSB, 1993). The track conditions resulted in the corners of the two cars impacting. On May 16, 1994, in Selma, North Carolina, an inter-city passenger train collided obliquely with a shifted intermodal trailer, fouling the passenger train's right-of-way (NTSB, 1995). On February 9, 1996, in Secaucus, NJ, a cab car led train, traversing a switch onto the main line, obliquely collided with a locomotive led train on the main line (NTSB, 1997). The corner of the cab car impacted the corner of the locomotive in this collision. A cab car is similar to a coach car, but is equipped with an operator's control stand. The cab car allows the train to be used in push-pull service. Fatalities occurred in all of these accidents.

The aim of vehicle crashworthiness is to minimize the potential for injuries and fatalities caused by the loss of occupant volume and by the deceleration imparted to the occupant during secondary impacts. In an oblique collision involving a locomotive, the short hood - a shell structure typically constructed using multiple material sheets - is the main load-resisting structural element. Proposed design modifications for improving crashworthiness should lie within the volume of the current designs. The context for this work is assessment of such proposals, not recommendations for design details to implement them.

The collision dynamics model described in this paper was developed to simulate accidents of the type in Selma. Figure 1 shows a schematic drawing of the initial conditions of the collision. The trailer struck the locomotive in the short hood away from its supports. The front, top, and sides of the short hood are made up of sheet metal plates that are welded together and to the main structure of the locomotive. The accident is described in greater detail in the Appendix. The primary purpose for the model was to evaluate the influence of changes in the locomotive design on the outcome of the collision.

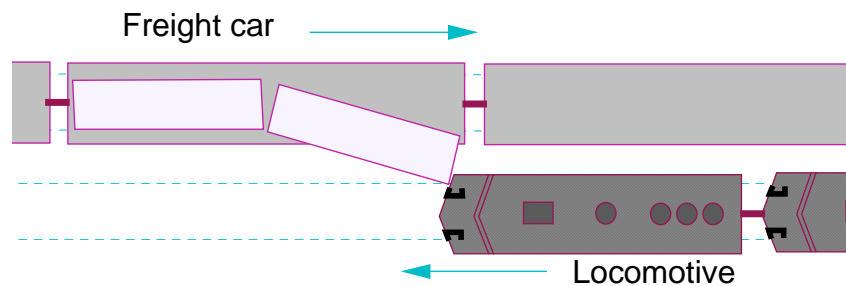


Figure 1. Initial conditions of Selma collision.

BACKGROUND

In a head-on collision, forces generated in contact reduce the forward speed of each vehicle. The process involves momentum exchange as well as energy dissipation when structural components are crushed. In an oblique collision, momentum transfer also instigates vehicle motion in the lateral

direction and may initiate movement vertically. The vehicles rotate, yawing about a vertical axis and rolling around a longitudinal axis. These vehicle motions can result in derailment. Contact interaction between the vehicles shifts in location as the cars move and deform. Vehicle contact is quite different from that of head-on collisions in which relatively strong underframe components engage. In oblique collisions, contact can occur above the underframe of the locomotive where the structure is largely sheet metal which is weaker and much less stiff than the underframe.

In all three of the cited collisions, the equipment essentially deflected past one another. While there was significant damage to the ends of the cars and locomotives in these accidents, the vehicles did not engage each other. This tendency toward deflection is a consequence of the long, slender geometry of rail cars and locomotives. Lengths of passenger cars and locomotives are typically 8.5 and 6 times their respective widths.

Figure 2 shows an impact force acting on a rigid body with a length 6 times its width. For such a body to deflect (turn away) from the impact force, the lateral component of the impact force needs to be only 17% or more of the longitudinal force. If the lateral component of the force is less than this value, the body will engage (turn into) the impact force. As a reference situation, gross motion in automotive collisions, in which the impacting bodies have length to width ratios of approximately 2, is much less sensitive to lateral force than in rail equipment collisions. In an automotive collision, the lateral force has a relatively short lever arm to develop a moment that turns the vehicle.



Figure 2. Schematic drawing of minimum lateral force component required to deflect a long slender body, drawn approximately to scale.

A simple rigid body model based on conservation of momentum can be used to illustrate the consequences of the vehicle geometry. Figure 3 shows two impacting bodies representing the locomotive and intermodal container at the instants just before and just after impact. Assuming that the motions are principally due to the impact force acting between the vehicles, each of these bodies rotates about its respective center of percussion. As long as the lateral component of the impact force is at least 17% of the longitudinal component, after impact both bodies rotate and translate away from each other.

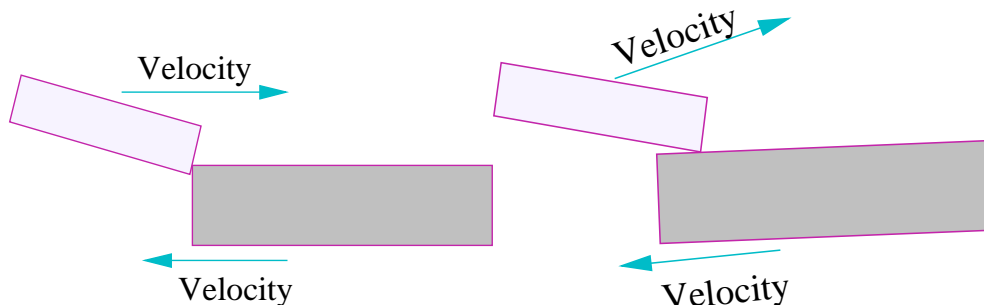


Figure 3. Planar view of oblique collision dynamics.

The closing speed of the Selma accident was estimated to be 177 km/h (110 mph.) Approximately 2.3 m (7.5 feet) of damage along the side of the short hood and operator's cab were observed on the lead locomotive after the accident. There was about 0.23 m (9 inches) of damage along the front of the short hood. The locomotive and container weigh approximately 1.165×10^6 N (260 kips) and 2.67×10^5 N (60 kips), respectively. The approximate dimensions of the locomotive are 3 m (10 feet) in width and 19.8 m (65 ft) in length. The container is roughly 2.4 m (8 feet) wide and 13.7 m (45 ft) long.

Neglecting the influence of the longitudinal force on the forward velocities of the bodies, the estimated duration of the impact is 50 milliseconds. For the locomotive and container to deflect past each other, the relative lateral displacement at the impacting ends of the bodies must be 0.23 m (9 in). For an average direction of 45 degrees relative to the centerline of the locomotive, the impact force required to move the end of the locomotive away from the end of container by 0.23 m (9 in) in 50 milliseconds is 2.04×10^6 N (458 kips.)

The duration of the impact was actually longer, at least in part due to the intermodal container slowing down during the accident. The trailing equipment behind the lead locomotive of the passenger train probably influenced that locomotive's speed, and potentially its trajectory during the collision. The effective mass of the impacted locomotive is less than its total mass. The suspension between the trucks and locomotive car body acts to isolate the trucks and traction motors that comprise approximately one-third of the locomotive's weight. Potentially significant lateral forces act on the locomotive through the flanges on the wheels. Derailment, which occurred during the Selma accident, is dependent upon the vertical wheel/rail force, as well as the lateral force. The vertical wheel/rail forces are, in turn, dependent on the roll motions of the vehicles. To account for these factors, a more detailed model is required.

A three dimensional lumped-mass modeling approach was adopted to incorporate the decisive features of the vehicle dynamics and collision deformation. Since the weight of the structure crushed during the collision is small compared with the weight of the locomotive, and most of the equipment remained essentially intact during the impact, deformation and energy loss can be well represented with discrete non-linear, inelastic springs. The mass of one-half the short hood of the locomotive in the accident is less than 1% of the mass of the entire locomotive. The trucks of the lead locomotive had essentially no structural damage, and neither did the trailing locomotive or its trucks. The intermodal container was destroyed during the course of the accident. However, it is impossible to tell at what point the damage occurred – during the impact with the locomotive or after. Reasonable assumptions are that the container acted as a rigid body during the impact and that it broke apart while it tumbled to a stop after the accident. The intermodal container was filled with cat litter. It is rationalized that the cat litter behaved like sand under impact conditions. The model is implemented in the ADAMS mechanical systems simulation software package (ADAMS, 1998).

A model of an oblique collision could be developed that simultaneously calculates the crush of the structure and the gross motions of the equipment. However, such a model would require representation of many details that have large uncertainties. No matter what modeling approach is used, some assumption is needed to define the direction of the impact force. For example, contact models employed in non-linear dynamic finite element codes such as DYNA3D, ABAQUS, and PAMCRASH are essentially friction models for the transverse component of the contact force. The surfaces of the rail equipment structure are typically ablated and gouged during an impact, and appliances are often torn off; a friction model of such phenomena is at best heuristic. The coefficient of friction, and perhaps other parameters, would need to be chosen such that the model predicted the outcome of the accident or some test condition. This approach has been applied with success in

analysis of automobile crashworthiness. Because the gross motions of automobiles are less sensitive to the lateral component of the impact force than the gross motions of rail equipment, they are less dependent on the modeling of the transverse component of the contact force and the choice of the coefficient of friction. In addition, automobiles cannot derail and are generally not coupled to other vehicles. Therefore less accurate determination of the gross displacements is tolerable in a model of an automobile collision than in a rail equipment collision.

APPROACH

The challenge in modeling such situations is to properly characterize structural and dynamic features of the colliding vehicles. The principal issue addressed in developing the simulation model of this collision scenario is the relationship between the lateral and longitudinal components of the impact force. For the short hood structure, the magnitude of the impact force is not sensitive to the direction of crushing (Tyrell, et al, 1999), i.e., the same amount of force develops whether the short hood is being crushed longitudinally, laterally, or diagonally. The relationship between the longitudinal and lateral components of the impact force was developed heuristically based on observation of the damage to equipment involved in the Selma accident.

The three-dimensional collision dynamics model is shown in Fig. 4. It has rigid body masses that represent the container, two locomotive bodies and two trucks for each locomotive. Only two-dimensional motion in a horizontal plane is allowed for the trailer. This constraint accounts for interaction with the floor of the flat car. There is no other connection between the trailer and flat car, an assumption that avoids coupling the mass of the flat car directly to the collision forces. Each of the masses for the locomotive bodies is allowed three translational and three rotational degrees of freedom.

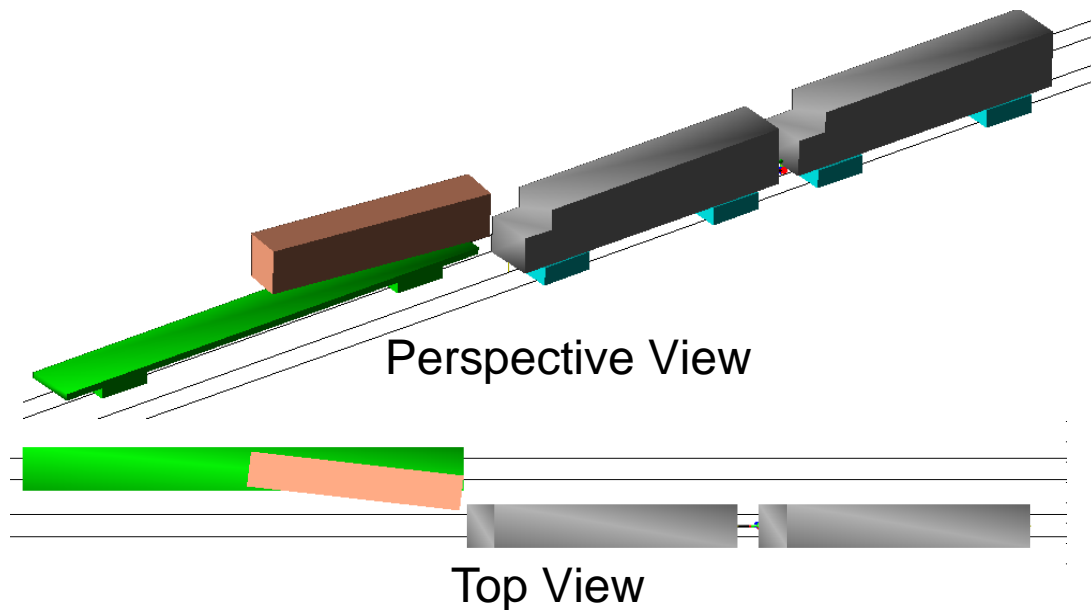


Figure 4. Schematic representation of the three dimensional locomotive model.

Contact between vehicles is modeled using spherical impact elements. These elements generate elastic restoring forces based on Hertz contact when the colliding surfaces try to penetrate one another. As the collision develops, the contact point can move along the sphere, adjusting the angle of the contact plane to account for changes in the direction of the net impact force. Representation of this behavior is necessary to model the transfer of momentum from purely longitudinal to the lateral components that push the vehicles apart and allow them to pass one another.

Collision between spherical mass particles is illustrated in the schematic diagram of Fig. 5. Just before impact, the two objects travel in opposite directions as indicated in Fig. 5a. The plane normal to contact is not perpendicular to the velocities. The contact angle depends on geometric details of the approaching vehicles: the distance between tracks, the shape of the facing surfaces and the angle that the intruding trailer has rotated outward before the collision.

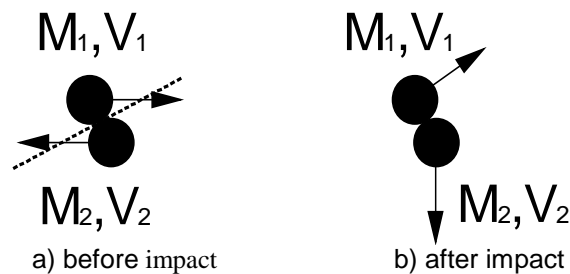


Figure 5. Illustration of contact plane and initial and final angles of velocity/momentum vectors.

In the locomotive model, the impact elements are connected by springs to the body that represents the bulk of the locomotive mass. These springs have non-linear force-displacement characteristics developed from a separate analysis of the short hood. This analysis uses a detailed non-linear dynamic finite element model of the short hood loaded by impact with a rigid body intended to represent the intermodal container (Tyrell, et al, 1999). The influence of impact direction, initial location of the impacting body on the short hood, and impact speed on the response of the short hood structure were examined. For loads applied well outboard of the collision posts, the results were not sensitive to the direction of load application and only mildly related to the speed of impact. Based on these results, the magnitude of the force in the spring is characterized by dependence on displacement from the initial position in the horizontal plane of the locomotive.

Figure 6 shows a typical result in which the response of the entire short hood is represented by plotting the applied contact force as a function of crush, the displacement of the rigid impact object. The details of the force-crush characteristic during the impact do not have an influence on the trajectories of the impacting bodies (Den Hartog, 1948). The principal influence on the trajectory of the bodies is the transfer of momentum from one body to another. Accordingly, the force-crush characteristic from the finite element analysis is smoothed to produce the force/displacement characteristic for the spring. An average, shown as the dotted line in the graph, is used to smooth the results to produce the force-displacement characteristic of the spring.

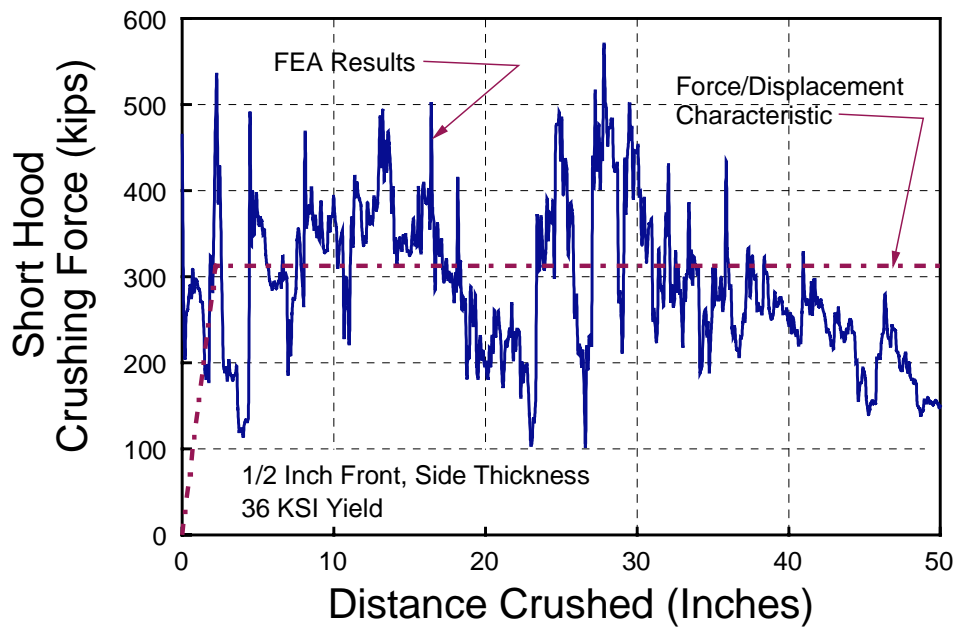


Figure 6. Typical force-crush characteristic for offset oblique collision.

The arrangement of contact elements was tuned to ensure the proper relationship between the lateral and longitudinal components of the impact force. The intermodal container was modeled as a single impact element, while three impact elements on each side were used to represent the short hood of the locomotive. Multiple spheres enable the model to account for designs more complex than typical short hood designs. A fourth impact element was used to represent the sub-base of the locomotive. Figure 7 illustrates the impact elements used to represent the locomotive short hood.



Figure 7. Impact elements along the locomotive short hood.

Effective mass, contact angle, stiffness and damping of the impact elements were chosen to produce the appropriate trajectories of the bodies. Initiating contact at roughly 7 degrees to represent a situation in which the container impacts at the corner of the locomotive, the vehicles remain in contact for 2.3 m (7.5 feet) along the locomotive for a closing speed of 177 km/h (110 mph). Values of 2.1×10^7 N/m (1.44×10^6 lb/ft) and 4.1×10^5 N-s/m (2.81×10^4 lb-s/ft) were assigned to the impact

stiffness and damping of the 1364 kg (3,000 lb), 0.615 m (2 ft) diameter contact spheres. To retain structural and dynamic symmetry, identical spheres were placed at each corner of the locomotive.

Figure 8 illustrates the features used for interaction of the lead locomotive with the colliding vehicle and trailing locomotive. The trailing cars in the consist do not have a strong influence on the damage incurred by the impacting locomotive. However, trailing locomotives must be considered to model the dynamics of the train (Mayville, et al 1995), since the strength of the main structure of the locomotive is significantly greater than the corresponding strength of the trailing cars.

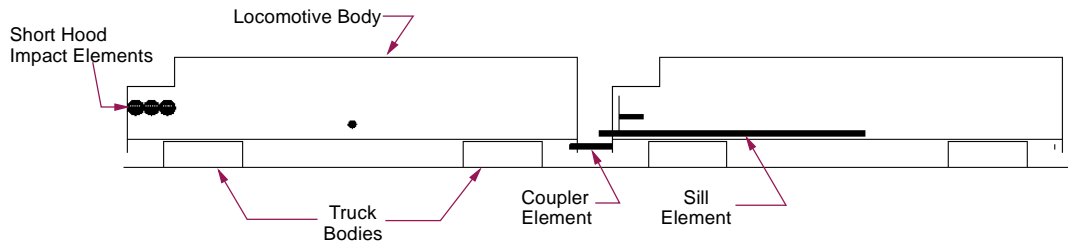


Figure 8. Locomotive and truck rigid bodies.

The secondary suspension between the trucks and locomotives is a combination of spring and damper elements that are linear for small displacements and represent compression and extension stops for large displacements. These elements transmit forces between the locomotive bodies and trucks in the lateral, longitudinal and vertical directions. The primary suspension guides the trucks along a track consisting of left and right rails laterally separated by 1.5 m (5 ft) and a defined path geometry, which is tangent in this case. Each truck has elements to transmit vertical and lateral forces to the rails, one for each rail. The maximum ratio of lateral to vertical force (L/V) that can develop in the model is 0.5. This is intended to be a truckside L/V that is capable of producing rail rollover (Blader, 1989). If sufficient lateral force develops and the lateral to vertical force ratio reaches 0.5, the truck will begin to displace laterally relative to the rails. After two inches of displacement relative to the rails, derailment is considered to have occurred due to rail rollover.

Table 1. lists the centriodal mass and principle mass moments of rotational inertia that were prescribed to represent the bodies of the locomotives and trailer. These values were adapted from a similar ADAMS locomotive model (Mayville, et al 1995) and the dimensions of the trailer specified in the scenario accident report (NTSB, 1995).

Table 1. Vehicle Inertia Parameters

Inertia Property	Locomotive (Mayville, et al 1995)	Trailer (NTSB, 1995)
Mass	84,821 kg (5,814 slugs)	$2.57(10)^4$ kg ($1.76 \cdot 10^3$ slugs)
Centriodal roll	$7.1(10)^3$ kg-m ⁴ ($5.6 \cdot 10^4$ slug-ft ⁴)	$2.84(10)^3$ kg-m ⁴ ($2.25 \cdot 10^4$ slug-ft ⁴)
Centriodal pitch	$1.5(10)^5$ kg-m ⁴ ($1.2 \cdot 10^6$ slug-ft ⁴)	$2.33(10)^4$ kg-m ⁴ ($1.85 \cdot 10^5$ slug-ft ⁴)
Centriodal yaw	$1.5(10)^5$ kg-m ⁴ ($1.2 \cdot 10^6$ slug-ft ⁴)	$2.28(10)^4$ kg-m ⁴ ($1.81 \cdot 10^5$ slug-ft ⁴)

RESULTS

The first target for the model was a comparison of predicted behavior with the accident scenario. Realistic representation of the crush of the front hood structure was the focus of this effort. Figure 9 shows the force-crush behavior used to describe the design of the locomotive in the Selma collision. Initially, the crush longitudinally and laterally is dominated by the sheet metal of the short hood. In

the longitudinal direction, after 0.615 m (2 ft) of crush a second impact element (see Fig. 7) is engaged that represents a frame structure needed to support the sheet metal in this locomotive design. For deformation greater than 1.23 m (4 ft), longitudinal load impacts the sub-base and increases the crush force to 2.2×10^6 N (500 kips). The effect of the collision posts is similarly represented for crush larger than 0.615 m (2 ft) across the front of the hood.

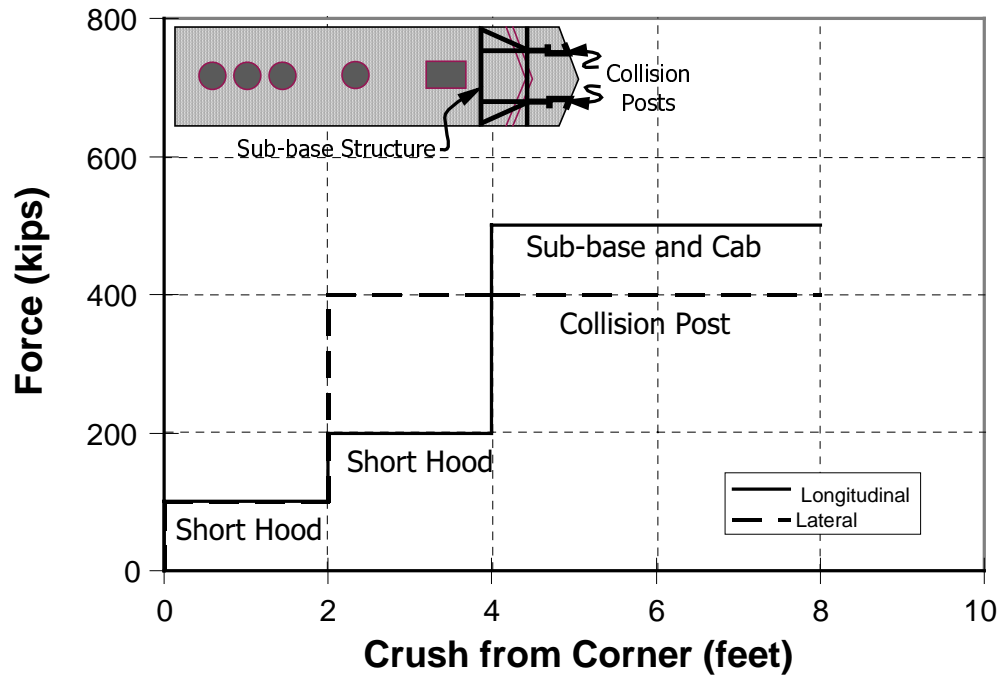


Figure 9. Force-crush characteristic of locomotive in Selma accident.

Figure 10 shows the influence of closing speed on the crush of the short hood and on the tendency to derail. As speed increases, crush of the short hood increases. Derailment occurs only if there is a lateral impulse adequate to move the front end of the locomotive a sufficient amount laterally. Lateral motion of the front end induces suspension forces between the car body and the truck necessary to laterally move the truck enough to result in derailment. The lateral component of impulse at 44 km/h (27.5 mph), where the locomotive does not derail, is roughly half the corresponding value at 88 km/h (55 mph), where it does derail. The time duration is similar for both cases. The average lateral force, however, nearly doubles since the crush distance is much larger at the higher speed. At 44 km/h (27.5 mph), only the short hood is crushed, while both the short hood and the sub-base are involved at 88 km/h (55 mph).

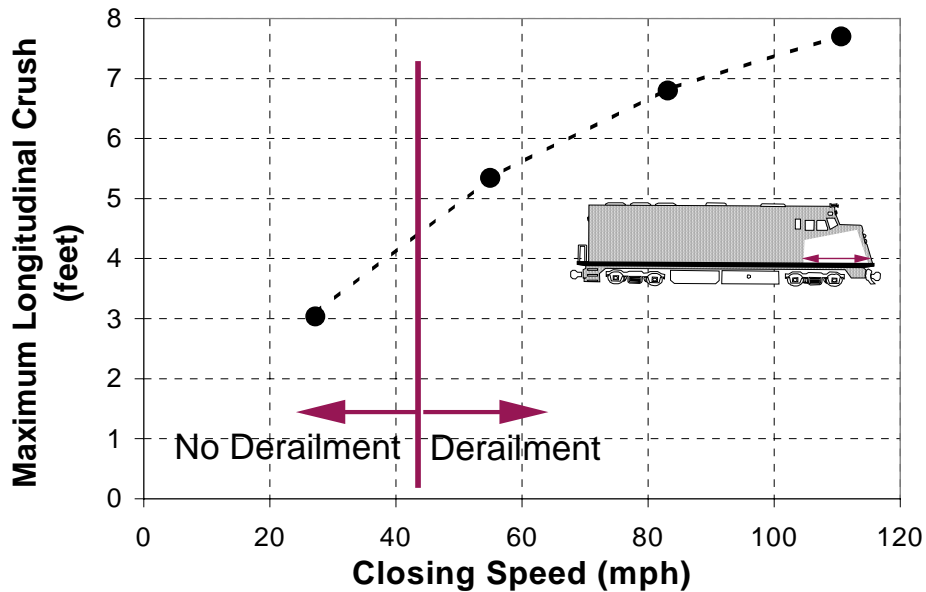


Figure 10. Short hood crush vs. closing speed, locomotive in Selma accident.

Predicted longitudinal and lateral deceleration time histories for the operator's cab are shown in Figure 11. The peak longitudinal deceleration is relatively low, less than 2 G's, while the lateral deceleration peaks at nearly 7 G's. These pulses could be used as input to a simulation of occupant response during the collision. From a structural perspective, the occupants are substantially weaker and lighter than the locomotive. Hence, the occupant dynamics can be calculated separately from component crush and train collision dynamics.

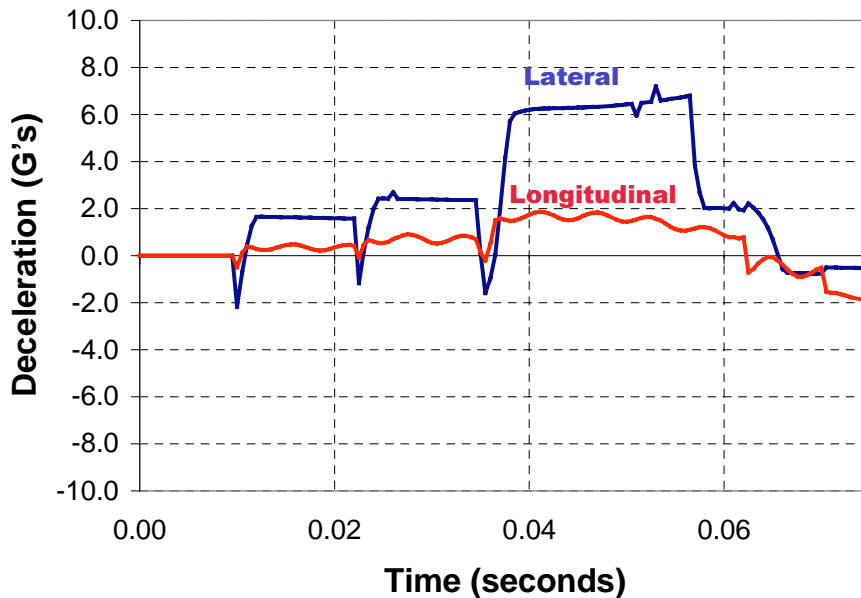


Figure 11. Predicted deceleration time history of operator's cab during Selma collision.

Although no analysis of the operator's response during the impact was carried out as part of this study, the comparison of these crash pulses to other study results suggest that the operator would be able to survive the deceleration during the collision of the locomotive with the intermodal trailer (Tyrell, et al, 1995). The accelerations associated with the operator's cab are relatively low during this impact. For reference, acceleration of an automobile during a 48 km/h (30 mph) barrier test typically exceeds 30 Gs (Federal Register, 1997). The locomotive in the Selma accident also derailed and rolled onto its side; the deceleration during the locomotive's impact with the ground may have been greater than the deceleration during the impact with the intermodal trailer. The likelihood of survival is also dependent upon the interior arrangement of the cab.

A second target for the model was to evaluate the effectiveness of modifications to the short hood design. Changes in the force-displacement characteristic of the connection between the crush element and the locomotive body were used to represent the structural modifications. Many different designs may result in the same force-displacement characteristic for the short hood, which in turn produce the same collision dynamics. With this approach, a force-displacement characteristic can be described a priori and a structure subsequently developed which produces the force-displacement characteristic. Analyses of the force-crush behavior of various short hood designs have been carried out (Tyrell, et al, 1999). The principal modifications considered were changes to the material properties and thickness of the short hood sheet metal. Since the focus was on the crashworthiness performance of the short hood, the container was raised sufficiently that it would not impact the sub-base. Only one impact sphere on each side of the locomotive (characterized with a force/crush characteristic similar to the one shown in Figure 6) was activated to model this type of structure.

The maximum safe crush of the short hood is estimated to be 1.5 m (5 feet). While less than the distance from the end of the short hood to the operator's cab, crush greater than this value would result in intrusion into the compartment. For this type of analysis, it is conventional to account for the volume of the crushed material. In oblique collisions, however, it is likely that most of the crushed material will move laterally, either inside the short hood or outside of the locomotive.

Figure 12 shows the influence of short hood crush strength on the closing speed required to cause 1.5 m (5 feet) of crush of the short hood. The graph compares two designs typical of current locomotives, represented by points at 4.63×10^5 N (104 kips) and 8×10^5 N (180 kips) mean crush force, to modified designs, the points at 1.13×10^6 N (254 kips) and 1.8×10^6 N (405 kips), respectively. The results suggest that current locomotive short hoods can be expected to protect the operator's volume in this type of collision up to closing speeds in the range of 38 to 55 mph. With hypothetical design modifications to the short hood, the simulation indicates that protection of the operator up to a closing speed of 153 km/h (95 mph) is feasible.

The locomotive is not predicted to derail for any of the cases shown in Figure 12. While the lateral impulse for these four cases is less than the impulse that will cause derailment, the case with the highest mean crush force considered predicts lateral displacement of the truck within 1 mm (0.04 in) of the value required for derailment.

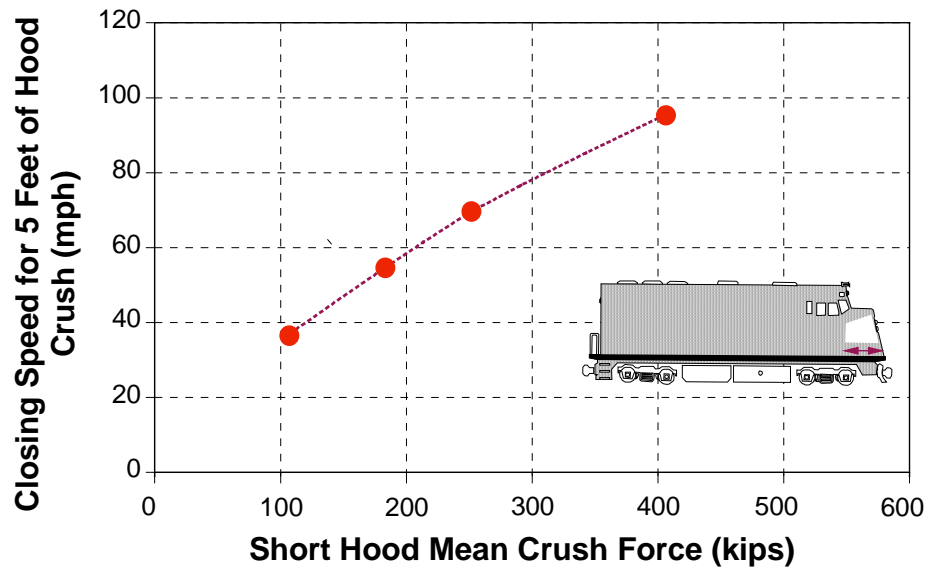


Figure 12. Influence of short hood mean crush force on safe closing speed.

SUMMARY

A three dimensional model of an oblique train collision with an intermodal container has been developed which simulates motion of the equipment involved in an oblique collision. The model is suitable for evaluating the influence of changes to the short hood design on the amount of crush incurred and on the deceleration of the operator's volume. This model has been used in a parametric study to compare performance of current short hood designs with hypothetical designs that have larger crush strength. Increased short hood strength provides better crashworthiness in this collision scenario.

Analytic models of impacting bodies that undergo crushing require detailed understanding of the mechanics that give rise to the lateral forces that are initiated after longitudinal impact of the vehicles. This lateral force is dependent upon the change in geometry that accompanies collapse of the structure as well as the nature of the contact between the impacting bodies. To fully understand this process, experiments are needed to measure separately the influences on lateral force of the structural collapse and the nature of the contact. Current planning includes research efforts to test short hood structures for verification of force-crush behavior and of how the lateral forces develop in oblique collisions.

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APPENDIX: INTERCITY PASSENGER TRAIN COLLISION WITH INTERMODAL TRAILER, SELMA, NORTH CAROLINA, MAY 16, 1994 (NTSB,1995)

An overhanging intermodal trailer on the northbound CSXT 176 freight train was obstructing the right of way of the southbound Amtrak passenger train 87. The northbound freight train was traveling approximately 56 km/h (35 mph) and the southbound passenger train was travelling about 120 km/h (75 mph). The forward trailer on the 51st car was overhanging the southbound track and engaged the lead locomotive of the passenger train. At the onset of contact, the trailer was above the deck and offset outside of the collision posts of the passenger train lead locomotive. The assistant engineer was killed during the accident and the engineer survived the accident with injuries. Figure A-1 schematically depicts the conditions that initiated the oblique impact.

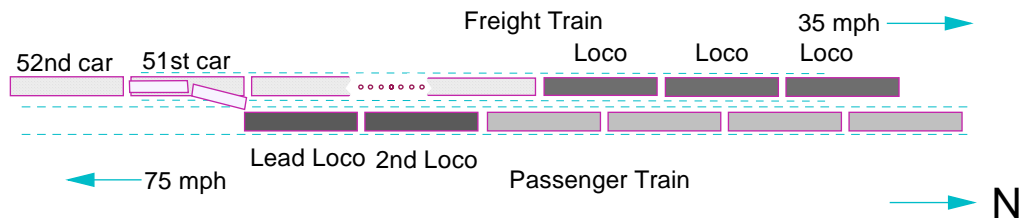


Figure A-1. Schematic of Selma oblique collision initial conditions.

Damage to the short hood began at the right front corner and extended along the right side to the control compartment. The lead locomotive in the passenger train derailed and rolled over, coming to rest its left side. All but one of the trailing cars, as well as the second locomotive, left the track, but remained upright. Only the last two cars in the freight train derailed and were damaged. The trailer, which was full of cat litter, burst open, spilling its contents along the track. The flat car carrying the intruding trailer came to rest about 12 m (40 ft) off the track in an upright position with the deck and end bent. Figure A-2 schematically depicts the conditions immediately after the accident.

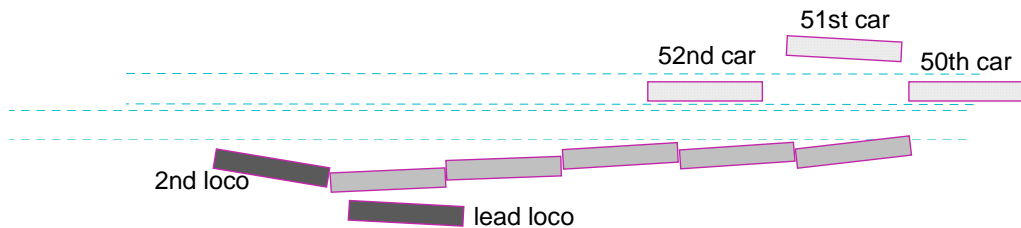


Figure A-2. Schematic of Selma oblique collision final conditions.

Figure A-3 illustrates the damage to the locomotive from the impact with the container. The container initially impacted the sheet metal of the short hood approximately .23 m (9 in) from the side of the locomotive. The damage extends back approximately 2.3 m (7.5 ft). For approximately the first 1.5 m (5 ft), the principal damage is to the short hood. For the remaining 0.8 m (2.5 ft) the principal damage includes the sub-base and the sheet metal on the side of the operator's cab. The sub-base is the structure, which provides the floor for the operator's cab and, beneath the floor, space for batteries and other ancillary equipment. The locomotive in the accident was a General Motors/ElectroMotive Division F-40PH.

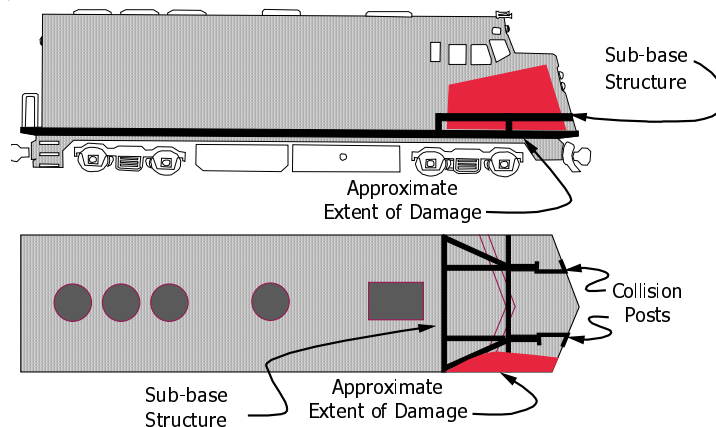


Figure A-3. Schematic drawing of locomotive damage from impact with intermodal trailer.